Sustainabot – Exploring the Use of Everyday Foodstuffs as Output and Input for and with Emergent Users

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ABSTRACT

Mainstream digital interactions are spread over a plethora of devices and form-factors, from mobiles to laptops; printouts to large screens. For emergent users, however, such abundance of choice is rarely accessible or affordable. In particular, viewing mobile content on a larger screen, or printing out copies, is often not available. In this paper we present Sustainabot – a small robot printer that uses everyday materials to print shapes and patterns from mobile phones. Sustainabot was proposed and developed by and with emergent users through a series of co-creation workshops. We begin by discussing this process, then detail the open-source mobile printer prototype. We carried out two evaluations of Sustainabot, the first focused on printing with materials in situ, and the second on understandability of its output. We present these results, and discuss opportunities and challenges for similar developments. We conclude by highlighting where and how similar devices could be used in future.

CCS CONCEPTS

• **Human-centered computing** → *Interaction techniques*; • **Computer systems organization** → Robotics; Embedded systems.

KEYWORDS

Robots, everyday materials, interaction, emergent users.

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1 INTRODUCTION

For a typical member of the CHI community, there are many ways of interacting with content stored or created on a mobile device in different, often more convenient ways. Whether this is achieved by switching to a larger digital display or projection, or perhaps using physical options such as paper or 3D-printing, it is easy to interact with and manipulate mobile content in more accessible or larger form factors when necessary. While mobiles are a core part of our device repertoire, then, we regularly accept that they are not sufficient on their own, and switch to alternatives.

For emergent users—that is, people in "developing" areas of the world who are just gaining access to advanced mobile technologies [1]—a mobile phone is very often the only device available [3]. Often, then, the act of transferring content to external displays or physical outputs that those in "developed" areas take for granted is not a viable option. Addressing this gap, previous work with emergent users has looked at ways of appropriating or sharing existing devices or features owned by others [18], or repurposing older, incompatible technologies such as outdated television screens[1]. In this work, however, we approach the problem from a different angle, and consider whether the materials already in and around users' homes might be able to be used to create novel interactive surfaces in existing environments.

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[1] e.g., TVCam: https://www.surrey.ac.uk/dwrc/funded-projects/tvcam

We present Sustainabot, a small robot printer that deposits everyday materials—foodstuffs, powders and so on—in patterns on a flat surface, controlled by a mobile phone. Consider the following scenario, which illustrates the concept:

> *Hina is helping her daughter with her geometry homework. She draws an equilateral triangle, but the screen is too small to be able to measure its angles. So, she slides her Sustainabot out of the corner of the device, pours in some salt and places the robot on a nearby table. The Sustainabot prints a material-based representation of the triangle, using dots and lines of salt to build up the image. As Hina manipulates the newly-created physical display with her fingers, the Sustainabot is able to capture her changes, signalling them to control apps or services connected to her mobile, such as a question based on the triangle just drawn. Afterwards, she sweeps up the salt to be used again, leaving no trace of its presence…*

Sustainabot provides a range of potential benefits over alternatives. Using an external screen requires significant power and physical space, which are less frequently available to emergent users. Further, the robot's output will persist without the need for a continuous power supply – a resource that is not guaranteed in many of the regions we have worked within. While conventional ink printers are an alternative, they require consumables which can be expensive and environmentally damaging. In addition, paper-based output does not afford the potential tangible, direct interaction that moving, piling or drizzling salt, grains and spices might.

The Sustainabot concept emerged and was developed through a series of co-design workshops conducted with emergent users in India and South Africa. This work led to a proposal for a mini robotic printer that creates output using everyday materials (such as rice or salt). We developed a series of prototypes of this design, ultimately creating the Sustainabot that we discuss in this paper. Sustainabot does not require external cameras for tracking, and can be used on any flat, horizontal surface (i.e., no special mark-up is required). Our current prototype focuses on the output elements of the concept. The robot prints with everyday materials by depositing them on the surface, making its output sustainable and reusable: when the image is no longer required, the owner can simply sweep up the material to use it again and again. In the rest of this paper we situate the research amongst previous work; describe and motivate the robot printer interaction and its co-creation and development; and, report on user experiments and output evaluation studies of the prototype we developed.

2 BACKGROUND

For emergent users, the number of ways of inputting and outputting digital content is often limited. Rather than the wide range of devices traditional users have access to, emergent users often have only a single device: a mobile phone. As Gitau et al. [3] and Donner [2] explain, the world of digital interaction *"does not run on mobile handsets alone"*. Other technologies that emergent users may own or share, such as a television, are output-only, and not interactive.

Previous work has uncovered the various ways that emergent users work around limitations in device access and interaction capabilities [24, 31]. Other research with emergent users has explored ways to widen the range of potential digital inputs and outputs available to such communities. Before the wide availability of mobile data-connections, projects such as the Spoken Web [10] used standard phone line connections to create interactive multi-user voice forums. Other approaches have extended the input or output space of existing devices on the phone itself. TapBack [20], for instance, recognised sounds from taps and scratches on the back of a device to allow gestural input even on basic phones. AudioCanvas [19] blended smartphone cameras with printed materials to provide local language audio annotations for documents and other physical media.

In a different approach, Pearson et al. [16] turned to look at far future technologies with emergent users, focusing on devices that, while currently beyond the reach of both emergent and traditional users, may provide particular benefits in emergent user contexts. It is in this same vein that we situate our work, considering Sustainabot as part of a potential future that may provide particular benefits for emergent users. In addition, we also note that while there is clearly more flexibility in interaction in the range of devices available to traditional users, there are issues of sustainability in terms of consumables (e.g., plastics, inks, or electronic waste when people are encouraged to renew their devices as often as once per year). We see this work, then, as a way to both address limitations in input and output capabilities for emergent users, but also as a reflection and potential opportunity around the throwaway culture that is embedded in the West [15].

Robots for input and output

Previous work has explored various ways of using robots for interaction assistance or enhancement. Much of the more recent research has been around mini robots that are able to 'swarm'; that is, to move in formation. Zooids [11] and UbiSwarm [9], for example, demonstrate a range of ways to physicalise data, interact with objects and create animated visualisations. While able to produce impressive, high-precision behaviours, including user-led movements, these approaches rely on an overhead projected pattern in order to track their movement. Other work has looked at similar interactions on interactive tabletops – for example, RoboTable2 [25] aims to teach robot programming; Touchbugs [14] vibrate to move across a tabletop; and, Tangible Bots [17] are capable of moving and augmenting existing tangible tabletop objects. In a different approach, Reactile [28] and FluxMarker [29] focused on enhancing tactile graphics for users with visual impairments, moving small markers on textured surfaces using an electromagnetic underlay for actuation. While each of these examples demonstrates mini robot-like systems for movement and input or output capabilities, each also requires external tracking or actuation assistance of some form in order to do so, and so is limited to marked-up or instrumented environments. Conversely, Sustainabot is able to navigate on any flat, horizontal surface, trading exact positional knowledge for flexibility in output location. Perhaps more similar, then, is the work of Guinness et al. [4], who appropriated off-the-shelf robots to extend desktop-based GUI applications, or the Anki Cozmo robot,[2] which is a playful mini personal companion able to move and respond to speech. Unlike Sustainabot, however, neither of these examples are focused around material interaction.

Turning specifically to printing using robots, Lee and Kim [12] provide perhaps the earliest example of a related system. Their design uses multiple robots that move around on a surface and draw lines to make up a print, though their interest was primarily in collision avoidance and evolutionary algorithms for optimisation, rather than output versatility. In commercial form, the ZUtA Robotic Printer printer[3] has been widely promoted, but is as yet unreleased. Rather than printing with ink, Sustainabot uses everyday materials as its outputs. More similar to our design, then, are various hobbyist projects that have created robot Rangoli printers. Rangoli is a decorative art form, common in India, in which coloured powders or petals are used to make intricate patterns on floor surfaces, often during Hindu festivals. One Rangoli printer, for instance merged a robot vacuum cleaner with an inkjet printer modified to drop powder,[4] but is large in size, and places material by moving the print head rather than the robot itself. Other Rangoli projects are entirely fixed in place, and so more similar to industrial robots[5]. Perhaps most related to Sustainabot is work by SenGupta and Deb [21], which uses a single sprinkler to draw with paint, but this system requires an overhead camera for tracking.

Moving beyond ink and Rangoli, there are several examples of using autonomous machines to create structures using materials. Shigemune et al. [22], for example, created self-folding printed origami. Turning to 3D printing, there are projects to both extend existing objects [30] or print entirely unrestricted in location and size using drones [5]. Igarashi and Inami [6] provide an overview of various examples in this space, while Kim et al. [8] look more to the future of such interactions, and speculate about ways to closely connect humans and machines in fabrication technologies.

Sustainabot focuses on creating reusable and temporary outputs with everyday materials. There are a small number of previous examples in this space. For example, Ghost Touch [13] used ultrasound to draw patterns into liquids or powders scattered on a surface. Graffiti Fur: [26] used a wheeled machine or handheld painting implement to sweep fabrics and carpets in the opposite direction to their natural flow in order to draw attractive patterns and images. An extension of this was able to draw similarly on grass [27]. Sustainabot is related to these systems, then, being able to repurpose ordinary objects into displays, but it does so by placing everyday foodstuffs rather than by modifying materials or coverings that are already on a surface.

3 CO-CREATION WORKSHOPS

In a project initiated in 2013, we have been working with emergent users to co-create future technologies that might more closely fit their wants and needs. Through a series of annual participatory design workshops in several countries, we have explored potential current and future interactions, generated scenarios, and evaluated prototypes in order to assess the suitability of the designs created. Complete details of the methodology undertaken are beyond the scope of this paper, though further details of the principles and approaches we have followed are given in Jones et al. [7]. In this paper, then, we focus solely on the aspects of each workshop that led to and shaped the Sustainabot concept.

Future-focused workshops (2015–2016)

We held a series of co-design workshops with 71 emergent users in Bangalore, Cape Town and Nairobi in May and June 2015 (cf. [7], Table 1). This was followed by a further series of workshops in June 2016 with 24 emergent users in Cape Town, South Africa. The sessions were focused on hands-on experimenting and conceptualising future technologies, and included scenario generation phases to develop potential future designs that were especially suitable in attendees' own lives. One of the most prominent themes connecting the range of scenarios that emerged over the two years was around sharing and reuse of resources – in particular, ways to share screens; and, ways to allow multiple people to use limited resources collaboratively.

After the June 2016 workshops we worked to develop prototypes of each of the scenario designs that were generated. In testing these with emergent users, the most successful were ones that focused on sharing and reuse of existing

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[2] https://www.anki.com/cozmo; [3] https://www.zutalabs.com

[4] http://members.tripod.com/nagendra_r; [5] https://youtu.be/b425VXnXYhY

devices; community connectivity; and, on combining existing devices to create linked interactive spaces. In the 2017 annual workshop, then, we narrowed the focus to explore more specific future technologies that might help develop these areas, and one of the technology groups we selected included small autonomous vehicles such as robot rovers.

Robot rover co-design workshops (2017)

In July 2017 we held a further series of co-design workshops with emergent users in Dharavi, a large slum in Mumbai, India. The design strand we report on here was focused on ways robot rovers might be used for future interactions.

We recruited 12 Dharavi residents (8F, 4M) in three groups of four people for sessions lasting approximately two hours in total. Meeting in a local community hall, we began the sessions by demonstrating an example robot rover (a simple remote-controlled buggy), and interactively explaining how it could be controlled by a mobile phone. Following this, we talked through each part of the group's typical day and activities (times of day; and, home, work or school, socialising), and asked them to think about how robot rovers might be used in each situation. This part of the session lasted about 30 min. We then went on a 45 min technology tour [23] to nearby streets and a public square. During this activity, we asked the groups to identify potential places where a robot rover might be used, to think about how it might help them in their own interactions in these places; and, to consider any issues with its use. Finally, we returned to the community hall to wrap-up and discuss the broad ideas and scenarios that had been developed. Each participant was given ₹500 as a token of appreciation for taking part.

Workshop outputs. During the discussion part of the workshop, the groups saw various potential use-case scenarios for a robot rover. There were two main themes in the ideas generated, in each case focused first around the robot's *autonomy*, and then around its *size*. Turning first to autonomy, participants discussed how a rover could help by delivering parcels to the right destination automatically, collecting children from school unattended, or, more generally, any type of automated manual labour assistance that would free up participants' time. All three of the groups independently raised concerns that such a rover would likely only be able to work indoors – they felt that Dharavi's busy streets and uneven ground would make it difficult for even the most capable rover to reliably navigate outside. At this point, each group turned to consider how an indoor-only rover might fit into their everyday lives, and began to focus on smaller devices that could be more useful in their own very compact homes. The scenarios generated from this point were far more focused on the groups' own everyday challenges and experiences. For example, participants imagined a rover that was able to be dropped down a narrow pipe to unblock clogged drains, or to crawl into tightly packed spaces to retrieve mislaid objects. Towards the end of a session, one of the groups of four older female participants discussed how a tabletop robot could help them by fetching utensils or measuring out quantities on the surface for cooking. This final idea led to a broader discussion around rovers interacting with everyday materials. In particular, we discussed the potential benefits of robot rovers that were able to pick up and set down everyday foodstuffs and other grains or powders. The group drew a parallel with intricately coloured Rangoli decorations, and wondered whether a small robot rover could create or enhance similar designs.

Discussion. After the workshops we analysed and reflected on the insights provided by co-design participants. We were intrigued by the potential use-cases of a small robot that could interact with everyday items. It was clear that participants saw the idea of picking and placing materials as attractive. Further, there were also clear links with the future-focused workshop themes from 2015 and 2016 around sharing and reuse, and on multi-device interaction in single-device households. We envisaged, then, creating a mini robot—Sustainabot—that could manipulate everyday materials as its inputs and outputs, taking instructions from a mobile phone. In this way, the robot could potentially provide some of the benefits of a large screen, without the associated power and space requirements. By repurposing materials that were already to-hand, it would remove the need for additional consumables, and by reusing materials repeatedly, it offered the potential to create low-cost, semi-persistent yet tangible interactive surfaces.

4 CONCEPT REFINEMENT WORKSHOPS

To further explore the potential use-cases for such a design, and to help uncover potential issues around interaction practicality, we ran a third set of workshops in December 2017 focused solely on the Sustainabot concept. We recruited 20 emergent user participants from slum areas around Mumbai, India. Here, as in all of the India-based studies of Sustainabot, participants had generally low personal and/or family educational attainment or literacy, and experienced other resource constraints such as limited income. Participants in this study were aged 18–40, and were all smartphone owners (or had regular access to a shared device), but not owners or regular users of other forms of technology such as laptops, tablets, large-screen televisions or printers.

The first 10 participants (7F, 3M) took part in a material creation workshop, while the second group (9F, 1M) followed a different procedure and were asked to evaluate the outputs made in the first session. The two sessions lasted around 90

Figure 1: A still frame from the stop-motion concept video used in the concept refinement workshops. The image depicts the Taj Mahal (see Fig. 2, bottom right), and was created using peppercorns. Participants watched as the drawing was made up, line by line, by the "robot" (here simply a small plastic cube), starting from the top left of the image.

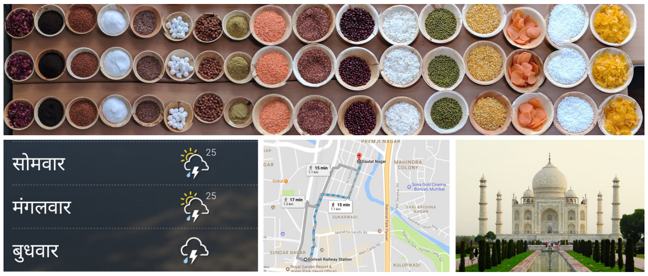

Figure 2: Top: the materials used in the Sustainabot workshops. From left to right: flower petals, instant coffee grains, nachani millet, salt, flax seeds, sweet makhana, chana chickpeas, coriander powder, masoor dal split lentils, patni rice, kidney beans, poha flattened rice, mung beans, toor dal split peas, uncooked papad, sabudana tapioca, cereal.

Bottom: the three projected images used as material drawing guides. From left to right: local weather forecast, map with directions, photograph.

minutes each, and both took place on the same day. Each participant was given ₹500 as a token of our appreciation.

As the refinement workshops were conducted before building the Sustainabot prototype, we created a stop-motion example scenario video to help illustrate the concept to participants. The video depicted a small "robot" creating an illustration using peppercorns (see Fig. 1), building up a representation of a photo of a well-known landmark line-by-line. In order to help stimulate participants' thinking around potential interaction materials, we also gathered a wide range of household foodstuffs and other readily-available items to be used in tasks during the workshops (see Fig. 2, top).

Procedure – material creation workshop

After an IRB-approved informed consent process, we began the first refinement workshop by dividing into three smaller groups (two groups of three; one of four participants), each working separately with a researcher. Each group began with a discussion of how participants currently shared content from their phone with others (e.g., passing phones around, connecting other devices, printing, etc.). Next, we showed the Sustainabot concept video (see Fig. 1), and asked participants to think about how they might use this robot to illustrate content from their phone. In particular, we asked participants to think about: i) what sorts of things would be created; ii) where they might create these outputs; and, iii) what materials such a robot might use.

In the next part of the workshop, we asked participants to manually create their own versions of potential robot-printed images using a range of materials that we provided (see Fig. 2, top). We did this by laying out a large sheet of paper on the floor of the room in a separate area for each group, and arranging a projection of a local weather forecast (see Fig. 2, bottom left) on to this sheet from above. Participants then spent five minutes working together as a group to create their own version of the projected image using any of the available materials. See Fig. 3 for an example of this process.

After completing the image, we asked participants about why they chose the materials they had used. Following this, we removed the projection to leave the material sketch on its own, and discussed how the group felt they could improve the image (e.g., what aspects were missing compared to the original projection, what parts could be changed, etc.). This task was then repeated with two further images – first a local map with directions, and then a photo (see Fig. 2, bottom centre and right). After the final iteration of the task we discussed more broadly with the group about material-based mobile interaction and potential change of the image over time, including both inputs and outputs.

Finally, to conclude the workshop all 10 participants came back together for a discussion about the session and their thoughts about the robot printer. We asked participants to choose which of the three types of images was most appropriate for printing with materials, and also to critique and suggest other potential use-cases and materials.

Procedure – output evaluation workshop

We began the second concept refinement workshop with an informed consent procedure, then explained the concept and showed the robot printer example video We then discussed as a group the potential use-cases, materials and locations for such a device. Participants were then asked to look at each of the drawings from the material creation workshop in turn. All of the material sketches from the previous workshop were left in place, without accompanying projections. For each material sketch, we asked participants to decide individually what the image might be representing; and, for the photograph, after seeing all three examples of the sketches,

Figure 3: Sketching with materials on projected images to explore use-cases. Participants were tasked to replicate a projected image in no more than 5 min using any of the available materials (Fig. 2, top) so that the sketch would still be recognisable when the projection was removed.

to vote on which was the best representation of the original image. Finally, we asked the group to suggest improvements to the images to make them more recognisable, and again critique and suggest additional use-cases and materials.

Results

It was clear that all participants from the first session wanted to—and did—regularly share with others in order to move beyond the limitations of their own devices. One participant had connected their phone to a television, and two had used printers at cybercafes, but for the remaining participants, passing phones around was the main way to achieve this. Participants' initial reaction to the Sustainabot concept video, then, was one of intrigue. Half of the participants had previous experience with Rangoli, and for most this was the first suggestion for potential use-cases. Other suggestions included leaving messages for family members, printing pictures or icons, and for children's play or school projects. The groups were clear, however, that due to the limited size of their homes, a tabletop, chair or small floor surface-based robot would be best. Turning to materials, there were a large number of suggestions, with the most common being dal (lentils), though most of those in Fig. 2 (top) were also proposed.[6] Other possibilities included using coloured sand or crushed crayons to expand the range of colours available, and employing dust or dirt from in or around homes.

The material sketching task was approached in a broadly similar way by each of the groups. Figure 4 shows all of the outputs from this part of the session. In general, participants tried to carefully and precisely replicate all of the details in the weather forecast and map tasks, whereas for the photograph they aimed for a recognisable replica of the image. Materials were chosen either for their visibility (e.g., larger grains for larger parts of the image), or for their relation to the projected content (e.g., a yellow cornflake to indicate the sun; white salt for clouds; colours to reflect the real shades in the photo). As the 5 min time ran out, they chose materials primarily for their speed of placing or scattering, however.

Figure 4: Material sketches created by participants in the concept refinement workshops. The first image in each row shows the projection overlaid; the remaining images are without this guide. Rows show, from top to bottom: local weather forecast, map with directions, photograph. The starred image (bottom right) was chosen as the best material representation of the Taj Mahal photo. (Note: annotations on the images were added at a later stage by a researcher.)

Turning to the output evaluation session, the images created in the first two tasks were very hard to recognise, while those produced during the photo task were relatively easy to identify. None of the participants in the evaluation session could fully interpret the images of the weather forecast or map, though one participant was able to read the names of days of the week in one of the weather sketches. As the creator groups explained in their own session, they had focused on creating precise aspects of the projected content, and it was hard to recognise these without context. They suggested using smaller grains, or tools, to help with more precise placement and to make these images of any real use.

For the photo, all of the participants in the evaluation group were able to recognise the depicted image. The switch to interpretation rather than replication during image creation helped make these examples more successful. Participants in the creation group also explained how their experience with the first two image tasks had helped them refine their technique in both selecting and placing materials, leading them to ignore more decorative parts of the image and focus on the critical aspects for recognisability.

In the group discussions at the end of both of the sessions, participants suggested a range of ways in which the printout

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[6] Note: participants made their suggestions before seeing the materials.

could be made interactive. For example, swiping parts of the material away or touching a specific part of the diagram could prompt pieces to be redrawn. For the map example, touching two places could cause the robot to print suggested routes. They also suggested that items on the print should be changed if they are updated on the phone – for example in changing a map over time with different coloured materials to show changes in traffic.

When asked to select the most useful use-case for Sustainabot of the three graphic types they had seen, both workshop groups voted for photographs. Overall, they appreciated the ability of the design to reuse materials, and when asked about the most suitable option, suggested that salt or sand would be best, as these materials are both cheap and readily available. Participants also noted that larger or more spherical grains were more difficult to use due to their tendency to roll on a surface. When asked to compare to existing methods, participants saw various benefits such as the printout's visibility in bright light, and the potential for very high precision of placement in comparison to Rangoli. However, both groups pointed out the temporary nature of the outputs – for example, one participant noted that a fan might blow materials away and make unexpected changes to the printouts.

Discussion

Participants saw benefits in the Sustainabot concept, but found that many of the diagrams they created using materials were hard to interpret. Perhaps influenced by this, the most successfully recognised type of output—photos—was voted as the most useful use-case for a robot printer. In their discussions, however, participants primarily focused on diagrams and infographic-type outputs. While these types of outputs were difficult for participants to create by hand, they are perhaps the simplest for a robot to systematically and accurately build up. Importantly, they are also likely to be the most practical. Although participants successfully relied on a wide range of colours to make their photograph representations recognisable, a robot printer is likely to be able to deposit only one type of material at once due its small size.

5 SUSTAINABOT HARDWARE

After the concept refinement workshops, we spent several months developing a series of robot printer prototypes inspired by participants' feedback and suggestions. The final design—Sustainabot—is able to navigate around and place material on-demand on any flat, horizontal surface, as shown in Figs. 5 to 7. Its body is a thin 3D-printed shell, the internal space of which is largely empty, making up its material hopper (approximately 50 cm^3, able to hold around 60 g of salt). At its base, Sustainabot encloses a custom circuit board for control and communication, a battery, and three small motors. Two of these motors power the robot's wheels, with a castor ball balancing this at the opposite end of the body. The third motor controls material placement, through a funnelled chute that is connected to the material hopper.

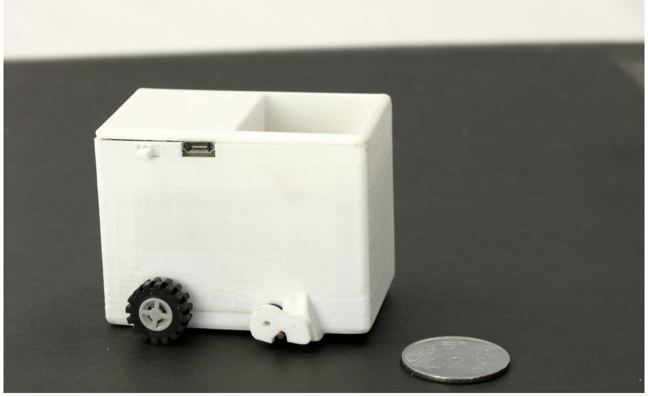

Figure 5: A Sustainabot, with a ₹2 coin for scale. The robot's exterior size is 6.3 cm × 3.9 cm × 4.8 cm (excluding wheels and material chute) – approximately the size of a matchbox. Its internal control and drive components take up approximately 10 cm^3 within the body, and the majority of the remaining internal space is used as a material hopper.

Figure 6: A Sustainabot printing the letters "CHI". This image is composed of still frames from a video of the device's movements, with the robot inverted in colour (i.e., black) so as to be visible against the salt it is dropping. The Sustainabot took 25 s to produce this 11 cm × 8 cm print (see video).

The user's interaction with the robot printer is made as simple as possible: other than refilling the hopper with printing material or connecting a charger, the device's only user-facing control is an on-off switch (see Fig. 5, next to Micro-USB charging port). All interaction and printing is handled via an accompanying Android app, which allows users to select from a range of inbuilt common icons (e.g., the home icon on a smartphone) or text, and converts them to either dot-matrix or line outputs that are automatically communicated to the device via Bluetooth. See Figs. 6 and 7 for a range of example outputs. Sustainabot is designed to print using salt, as shown in these images, but can also use a range

Figure 7: Sustainabot outputs, showing five examples made using the dot matrix printing approach, and one example of the line-based method (bottom right). Top: basic icons (arrow, cross and tick). Bottom left and centre: more complex diagrams (house and person). Bottom right: text ("Hi").

of other similar materials. We chose salt as the primary material due to its lower tendency to move after being dropped on a surface. Many other potential printing materials (such as poppy seeds, semolina or sand) are more prone to rolling out of place on the printing surface, even when dropped from the low height of the hopper chute (approx. 1.5 mm).

Participants in the initial co-design workshops envisaged a robot rover that was able to both pick up and set down everyday foodstuffs. Constructing Sustainabot, we made the choice to implement only setting down of material, as picking up materials would have required a far larger robot, less attractive to users. We felt that directly pouring grains into the robot from a packet was a worthwhile trade-off (rather than, e.g., emptying a bag of materials onto a surface and having the robot subsequently collect these).

Technical design

To create Sustainabot we designed a custom control board, of which the key components are an 8-bit microcontroller, a 128 kB EEPROM chip for storing commands, a MEMS accelerometer and magnetometer, a recharge circuit and three DC motor drivers. The control board is powered by a 300 mA h battery which gives several hours of runtime, and is also connected to an external Bluetooth module that provides communication. Sustainabot uses three 700:1 planetary-drive geared motors, which are both lightweight and provide enough torque to move a small robot. The two drive motors are pulse-width modulated to achieve a high degree of accuracy in movement, which is essential for printing high-quality outputs. To compensate for micro size variations between motors, a one-time calibration procedure (on initial construction) ensures that the robot moves in a straight line.

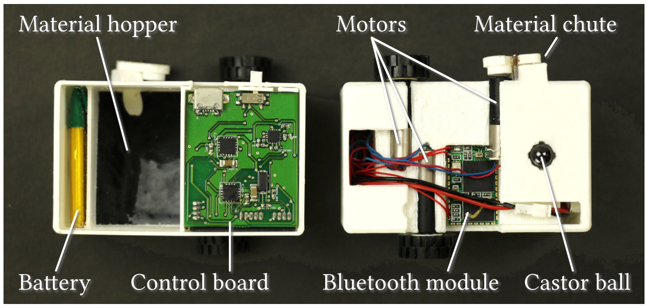

Figure 8: Sustainabot internals. Left: view from above; right: view from below. Both robots have their external casing removed to show the internal circuitry and components.

Sustainabot is capable of navigating surfaces using either compass headings or dead-reckoning. When in heading mode, the internal compass is automatically calibrated for each new surface in use – the robot rotates one whole turn to map out the magnetic field in the two axes parallel to the ground. However, this mode is more susceptible to external influence from ferrous materials in, for example, table fixings. In most cases dead reckoning navigation and movement is sufficient to create accurate outputs (e.g., see Figs. 6 and 7).

Printing material is gravity-fed from the hopper through a chute that protrudes from the side of the device. This design ensures that Sustainabot is able to print lines or dots of material very close to each other without disturbing their appearance by driving over them. The chute's cover can also be opened or closed by a configurable amount in order to allow for variable sized drops, or variable width lines.

The robot printer has two modes of operation – either receiving instructions or executing a stored list of commands. In receiving mode, Sustainabot listens constantly for configuration parameters (such as calibration settings) or movement commands. Configuration parameters are acted on immediately, whereas movement commands are added to a list in memory. After the complete command list for a printout is received, the robot is instructed to switch modes, and it then actions its current list of commands before returning to listening mode to await further instructions. Approximately 32,000 commands can be stored in this way (as an example, the illustration shown in Fig. 6 required 40 commands). Several of the available commands are designed to optimise complex movements (such as moving into a parallel position, drawing a dot, etc.) into a single instruction with a multiplier in order to speed up communication with the robot for repeated actions. Sustainabot is also able to change various configuration aspects on-the-fly to allow more flexible outputs. For example, slowing down one wheel while dropping material allows the robot to turn in smooth curves. An example of this method of operation is illustrated in Fig. 6.

Figure 8 shows the internal design of Sustainabot. In order to help stimulate further exploration of the potential for printing with everyday materials, we have released the robot's hardware and software designs and source code as part of an open-source material printing toolkit.[7]

6 SUSTAINABOT EVALUATION 1

After finalising the Sustainabot design we planned a study to evaluate the robot with emergent user participants, again taking place in Mumbai, India. Our original intent was to deploy 10 Sustainabots in users' homes for a week-long evaluation, but during preparation for this trial we encountered several challenges, as detailed below, so adjusted the procedure. Ultimately, to address these issues we chose to revise the design and conduct a similar study to the output evaluation workshop detailed in Section 4, but with outputs created by a Sustainabot, rather than manually by participants.

Deployment challenges

In preparation for the planned deployment, we constructed 10 Sustainabots, and designed a simple multi-day trial in which we intended to ask participants to use the robot printer at least once per day to print an item of content selected from their own mobile phone. In the days leading up to the deployment, however, each of the Sustainabots began to exhibit problems printing accurately. After investigating, we discovered that the castor ball that the robot relies on to allow it to move using only two drive motors was rapidly rusting in Mumbai's humid climate. In our original design we had chosen to use a solid steel ball, as its weight helped the robot to move steadily when carrying varying quantities of print material. Now unable to rotate smoothly, this corroded ball was stopping each Sustainabot from moving in the even and parallel lines required to create accurate outputs. We were able to solve the rust issue for one robot by polishing and lubricating its castor ball, but found that the problem rapidly reoccurred. Unable to replace the steel balls in all robots at short notice, we instead elected to modify the study design to use the robot printers only in a lab setting.

Method

We recruited 16 emergent users (11F; 5M; 11 with prior Rangoli experience) to participate in a lab study of Sustainabot's outputs. Following a similar method to that used in the earlier output evaluation workshops, we created three example prints with salt using a Sustainabot, and asked participants to state what they thought each one represented. Each participant undertook this task individually. The three printed images were, in order: a house, an arrow, and a person (as displayed in Fig. 7). After this task, we showed participants a Sustainabot, and asked them to select on its accompanying app from a range of simple icons, then watch it print out the chosen image. Finally, we asked participants: i) where in their house they might print using the robot; ii) what materials they might use; iii) any problems they foresaw with using the robot; and, iv) to show us an image on their phone that they could print with the robot. Each study session lasted around 20 min, and participants were each given ₹700.

Results

As in the earlier workshop, after seeing the robot printouts, participants' immediate thought was of Rangoli. Six participants correctly identified the house image, 14 recognised the arrow icon, and 12 identified the person.

Unexpectedly, over the course of the tasks, the printouts began to noticeably change in visual appearance: the salt absorbed moisture from the air and slowly liquefied. While participants suggested similar print locations and materials for the robot to those from the groups in our earlier workshops, then, they had criticisms, understandably, of its use of salt. In the hot and humid climate, there were suggestions for turmeric powder or mustard seeds as alternative output materials that are less-susceptible to absorbing moisture.

Despite this drawback, when watching the robot create images in the second part of the study, participants saw value in its speed and precision in comparison to manually-created material designs. In their own suggestions of outputs to print there were requests for writing, but also for more creative designs such as flowers, animals and photos of nature. They emphasised, however, the need for the robot to be accurate in its printing, especially of intricate details, and noted a requirement to be able to cope with uneven surfaces.

Discussion

The person and arrow outputs used in this study were relatively reliably recognised by participants. However, only a minority of participants were able to identify the house icon from the robot's printout. We suspect that this result was due to the unfamiliarity of the house icon in participants' experience – note, for example, that on the smartphones participants owned the Android home icon is a circle, rather than the house outline of previous versions.

We encountered several challenges over the course of the lab study. Using a castor ball susceptible to corrosion was a design flaw, subsequently corrected. More interesting was the behaviour of the printed outputs in the humid environment. While this might be seen as a disadvantage in many situations, one participant pointed out that she particularly liked this aspect: messages delivered by Sustainabot automatically disappear over time, adding a secrecy aspect, and emphasising the temporary, ephemeral nature of the output.

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[7] See: https://github.com/reshaping-the-future/sustainabot.

7 SUSTAINABOT EVALUATION 2

After the lab study, we revised the Sustainabot design, replacing the metal castor ball with a smaller ceramic version, removing the risk of rust causing the ball to seize. Using this refined version, we recorded videos and took photos of the final output of the robot, and used these as part of a facilitated workshop. We chose this method to allow us to trial the system in different locations and focus on the prototype outputs rather than any environmental constraints. 23 emergent user participants from Mumbai (19M; 4F), aged 18–45 were recruited for an IRB-endorsed study. Participants met with a researcher in groups of 3 or 4, and were firstly shown a video of the robot printing 'Hi', as illustrated in Fig. 7. Next, participants were shown, one-by-one, the tick, arrow, person and house icons in Fig. 7. After each image, participants were asked, individually: i) what did they think the image was showing; and, ii) after being told what it was meant to represent: to what extent did it look like that object (on a Likert-like scale of 1–7; 7 high). Finally, we showed another video of the robot, this time printing the house icon, and asked participants to reflect on: i) the situations in which Sustainabot could be useful to them; ii) what types of content they might use it to print; iii) where in their house they might use it; and, iv) what materials might be used. We also asked participants to think of any potential problems using the robot, and offer any suggestions for improving the printer. Participants were compensated with ₹500 for their time.

Facilitated workshops results

Table 1 (India) shows the accuracy of participants' object recognition, and also the average similarity score given for each object after being informed about its intended representation. The face and house icons were recognised with perfect accuracy, with the arrow and person slightly lower, and the tick the hardest to recognise. All of the participants who did not recognise the tick answered that it was the letter 'J', however, perhaps suggesting unfamiliarity with the tick symbol itself. Turning to the discussion that followed the task, 14 participants suggested to use the robot for creating Rangoli patterns, but there were also other more creative suggestions such as a tabletop messenger robot, or for a novel way of marketing. Participants felt that emoji characters and icons or diagrams would be the most useful applications for the robot, with photos also commonly requested, and felt that a table, floor or space in front of their house would be the most appropriate locations (e.g., for messages or notes). Four participants also suggested to use the robot on a wall, adapting its design to use a pencil rather than dropping materials. Finally, in terms of improvements to the device, there were requests to increase the speed of its drawing, and also to draw diagrams using mainly lines, rather than dots.

Table 1: Emergent user ($n = 23$) and UK ($n = 144$) recognition study responses, showing the percentage of correct definitions, and the rating for object accuracy (Likert-like; 7 high).

	India		UK	
	Correct (%)	Rating	Correct (%)	Rating
Tick	65	5.4	78	5.5
Arrow	91	6.5	100	6.7
Person	83	5.0	96	5.3
Face	100	5.6	97	5.1
House	100	6.3	97	5.5

Using Sustainabot in additional contexts

In order to explore whether the robot printer might have uses outside of its designed context, we conducted the same recognition study as in the facilitated workshops, but with participants who were not classed as emergent users. This study, undertaken in the UK, followed an identical procedure to the facilitated workshops, but was presented as an online questionnaire. We received 144 valid responses (80F; 63M; 1 undisclosed), from participants aged 18–65. Participants were not compensated for completing the questionnaire.

Results. Table 1 (UK) shows the results from the online questionnaire. Due to the variety of entries, we defined correct responses as those that either gave the exact description in their response (e.g., *"tick"*), or those which described in more detail, but had the same meaning (e.g., *"dots forming a tick shape"*). Other responses were classed as incorrect. Similar to the facilitated workshops, there were responses to the tick diagram suggesting it was the letter 'J' (7), but many of the other icons' incorrect responses were more elaborate, ranging from 'scarecrow' to an individual's name for the person, 'dinner plate' for the face, and 'sailboat' for the house.

Use-case ideas were almost entirely related to children, toys or education. Text and icons were the most commonly suggested types of suitable output, with the kitchen being the most preferred location, perhaps due to the use of salt. Sugar, sand and flour were also suggested as printing materials.

Improvement suggestions were primarily focused around the temporal nature of the printer's output, and its potential messiness, whether through external factors (such as dampness or wind) or simply due to the output being constructed of material rather than ink. Similar to the facilitated workshops, participants suggested using lines rather than dots, and increasing the speed of the robot. There were also interesting suggestions for using the robot in narrow spaces to manipulate materials, or in chemical laboratories, or ways to expand the range of colours available (e.g., by colouring the salt as it is placed). Finally, there were also ideas for varying the size of the outputs to make diagrams more detailed.

Discussion

Considering the results of both the facilitated workshops in India and the same recognition study in the UK, we see that participants were able to successfully identify images made using Sustainabot. The least recognised output (the tick) was made up of the lowest number of salt dots of all images, perhaps inevitably leading to greater ambiguity. In terms of use-cases and suitable locations, participants in Mumbai suggested only surfaces (e.g., table, floor, outside house), while UK participants tended to refer to rooms (mainly the kitchen). This may be because Mumbai participants have far smaller and limited home spaces compared to those in the UK; and, the floor is commonly used for Rangoli patterns – Sustainabot's small size and flexibility may be a benefit in such environments.

8 CONCLUSION

When traditional users think about displaying content from their mobile in other forms, they will likely consider a diverse palette of possibilities from paper to large high-definition screens. For the emergent users that have driven the innovations presented here, such options are usually out of reach. Our studies have illustrated the possibilities of using everyday materials as the basis of systems to extend mobile display capabilities in these contexts. These materials have the advantage of being affordable and sustainable, both through appropriation and reuse and their relatively environmentally friendly nature compared with, say, disposable inkjet cartridges. Food is inherently recyclable, while inks and paper are not always so. Food-based diagrams made with Sustainabot are also still edible after printing; and, unlike screens, physical material printouts require no energy post-production (in a similar way to E Ink).

Sustainabot is a first prototype to provoke creative design. Our open source material printing toolkit[8] aims at enabling others to take these and other outputs forward. Currently a Sustainabot robot costs around £100 to manufacture, but the price would be a fraction of this if commercially produced (in contrast, consider, for example, the cost of a desktop printer, with ongoing ink or toner costs). Future iterations might address both technical challenges (as highlighted earlier in this paper); and, extend the capabilities of the system. For example, consider the range of possibilities for potential permanent outputs, such as printing with sugar and caramelising, or printing with coloured Rangoli powders and moistening. There are also many wider extensions possible, such as the use of alternative materials; enabling layering of outputs, for instance by dropping peppercorns on top of a previously printed salt circle; and, providing interactive capacities by, for example, using the mobile phone camera to take a picture after the user has manipulated the printout, and then using Sustainabot to edit the output in response.

Finally, the work also highlights potential benefits of such approaches for designers and developers focused on very different contexts. Consider, then, this scenario:

> *Ben is sitting at home in San Francisco with his family. His friend in London has sent him a Sustainabot message. As the robot starts to print, the group looks on in delight as an image emerges, shouting out suggestions as to what is being delivered. At the end of the day, the family entertain their neighbours to a meal, and the Sustainabot image acts as a natural centrepiece and conversation starter…*

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